Gravitational lensing and modified Newtonian dynamics

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Abstract

Gravitational lensing is most often used as a tool to investigate the distribution of (dark) matter in the universe, but, if the mass distribution is known a priori, it becomes, at least in principle, a powerful probe of gravity itself. Lensing observations are a more powerful tool than dynamical measurements because they allow measurements of the gravitational field far away from visible matter. For example, modified Newtonian dynamics (MOND) has no relativistic extension, and so makes no firm lensing predictions, but galaxy-galaxy lensing data can be used to empirically constrain the deflection law of a MONDian point-mass. The implied MONDian lensing formalism is consistent with general relativity, in so far as the deflection experienced by a photon is twice that experienced by a massive particle moving at the speed of light. With the deflection law in place and no invisible matter, MOND can be tested wherever lensing is observed.

Keywords: gravitational lensing – gravitation – dark matter

1 Introduction

In the time since the discovery of the first multiply-imaged quasar (Walsh, Carswell & Weymann 1979), gravitational lensing has become one of the more powerful tools available to astronomers. The main advantage of lensing as an astronomical probe lies in its simplicity – the light deflection properties of a lens depend on just two things: its mass distribution and the nature of gravitational physics.

The success of general relativity (GR) – and, in the appropriate limits, Newtonian gravity – is such that lensing is almost always used to investigate the distribution of matter in the universe. The fact that, for example, cluster lensing cannot be explained by the visible galaxies and gas is then taken to be strong evidence for the preponderance of dark matter. There is, of course, a great deal of evidence that the universe is dark matter-dominated (e.g., Trimble 1987), but the lack of any non-gravitational detection of dark mass makes it an assumption that should continue to be tested by all available means.

The alternative possibility is that GR is only valid in the small-scale, large-acceleration regimes in which it has been experimentally (as opposed to observationally) tested. The majority of direct

tests have been within the Solar system, but measurements of time delays in binary pulsar systems (Taylor et al. 1992) have also verified GR. The degeneracy between the form of the gravitational acceleration and the distribution of mass is such that GR remains an assumption on galactic (and greater) scales. If it is hypothesised that there is no dark matter, then it is possible to determine the nature of gravity on these large scales from lensing or dynamical observations. Aside from their tendency to rely on assumptions of equilibrium, dynamical measurements are subject to the more fundamental limitation that the gravitational field can only be probed in regions where there is visible matter. By contrast lensing can be used to measure gravitational effects well beyond the luminous extent of the deflector(s). Further, if such measurements can be made sufficiently far from the lens[1], its internal structure becomes unimportant, and the lensing data uniquely constrains the deflection law of a point-mass. This is a potentially powerful technique that only breaks down at angular scales so large that the effects of other deflectors along the line-of-sight become important.

These methods can be used to determine the deflection law of a point-mass empirically (Mortlock & Turner 2001a) or to test a particular theory. For example Mortlock & Turner (2001b) investigated gravitational lensing within the framework of modified Newtonian dynamics (MOND). A combined approach is taken here, using MOND as an illustrative example. After explaining the principles of the theory (Section 2), a robust deflection law is derived from galaxy-galaxy lensing data (Section 3). The future prospects for more rigorous tests are then discussed in Section 4.

2 MOND

MOND (Milgrom 1983) hypothesises that the inertial mass of a particle is decreased when it is subject to an acceleration much weaker than a critical value, $a_0 \simeq 1.2 \pm 0.1 \times 10^{-10}$ m s^{-2}. In its purest form a MONDian universe contains no dark matter, and, remarkably, this simple model can explain the dynamics of galaxies and clusters (McGaugh & de Blok 1998), as well as the observed power spectrum of cosmic microwave background anisotropies (McGaugh 2000).

MOND is, of course, highly unconventional and the variation of inertia would be very difficult to integrate into the current broader understanding of the physical world. This fact alone is sufficient to convince many that it is extremely unlikely to be correct. However, even if one takes this (anti-empirical) point of view, MOND provides a potentially revealing opportunity to test the depth and robustness of modern science's observational knowledge of the universe. If it is not possible to contradict such a simple but seemingly outlandish and improbable hypothesis, how much confidence should be placed in more conventional explanations of the observed universe?

Another difficulty with MOND is that it is not a complete physical theory, lacking a relativistic extension, and thus making no definite predictions for light deflection (Milgrom 1983; Bekenstein & Milgrom 1984). The natural Ansatz for MONDian lensing is, as in GR, that a photon experiences twice the deflection of a massive particle moving at the speed of light (Qin, Wu & Zou 1995). This hypothesis gives qualitatively reasonable predictions (Mortlock & Turner 2001), but the effects of extended and multiple deflectors are somewhat ambiguous. However, the gravitational properties of an isolated point-mass, M, are well defined: the effective force law matches the Newtonian form for $r \ll r_{\mathrm{M}} = (GM/a_0)^{1/2}$, but falls off as r^{-1} for $r \gg r_{\mathrm{M}}$. The details of the physics for $a \simeq a_0$ are unspecified, but unimportant in the absence of high precision measurements. Integrating this acceleration along the line-of-sight gives the (reduced) bending angle, $\alpha(\theta)$, which matches the Schwarzschild form for small impact parameters [i.e., $\alpha(\theta) \propto \theta^{-1}$], but is constant beyond $\theta = r_{\mathrm{M}}/d_{\mathrm{od}}$. (Here d_{od} is the angular diameter distance from observer to deflector, which is not

[1]Note that, in the absence of dark matter, it is only the visible extent of the deflector that is relevant.

formally defined in MOND.) The deflection angle is not directly measurable, but the distortion of images and the (total) magnification of sources can be calculated directly from $\alpha(\theta)$, and these are observable.

3 Observational constraints

Gravitational lensing observations range from light deflection by the Sun, through microlensing in the local group, to the multiple imaging of high-redshift sources. If it is assumed that there is no dark matter then all of these observations place constraints on the nature of gravitational light deflection, but only some represent clean and powerful probes of MOND, whereas others are clearly within the Newtonian regime, or require the untangling of the combined effects of multiple deflectors. These issues are explored more fully by Mortlock & Turner (2001a), but it is clear that galaxy-galaxy lensing observations offer by far the best opportunity to make interesting inferences from available data.

Galaxy-galaxy lensing, the weak tangential alignment of distant galaxies caused by their more nearby counterparts, has been used to weigh the dark matter distributions of the foreground deflectors (e.g., Brainerd, Blandford & Smail 1996; Fischer et al. 2000). The results are all consistent with galaxies having large isothermal haloes extending to at least several hundred kpc. Interestingly, no upper limit has been placed on the halo size, despite the fact that a systematic distortion has been measured out to ~ 1000 arcsec, far beyond the visible extent of the foreground galaxies (only a few arcsec). Thus, under the no-dark matter hypothesis, these data represent an ideal means of measuring the deflection law of what is effectively an isolated point-mass. Even without performing any further analysis, the fact that the lensing data are consistent with rotation curve measurements in GR implies that the relationship between the deflection of massive and massless particles must be the same in MOND (or any other theory).

More quantitatively, Fischer et al. (2000) fit the shear signal around $\sim 3 \times 10^4$ foreground galaxies by

$$\gamma_{\rm tan}(\theta) = \gamma_{\rm tan,60} \left(\frac{60 \text{ arcsec}}{\theta} \right)^{\eta}, \tag{1}$$

with $\gamma_{\rm tan,60} = 0.0027 \pm 0.0005$ and $\eta = 0.9 \pm 0.1$. Figure 1 shows this fit to the data, along with the predictions of GR (assuming no dark matter) and the MONDian lensing formalism described in Section 2. The MONDian results (which imply $\eta = 1$) are clearly consistent with the data,[2] although there is some ambiguity in the normalisation, as the mass-to-light ratio of the deflectors are not known with great certainty (Mortlock & Turner 2001b). Thus the properties of MONDian point-mass lenses must be considered completely (if approximately) defined. It is not clear, however, that the entire derivation of the deflection law given in Mortlock & Turner (2001b) is verified, and so the lensing properties of more complex deflectors remain unknown, although future investigations should shed some light on this matter as well.

4 Conclusions

MOND, an alternative theory of gravity (or inertia), has been able to explain the dynamics of massive bodies in terms of visible matter where Newtonian physics requires large amounts of dark matter. However MOND has no relativistic extension and so makes no predictions about gravitational lensing. Here the opposite approach has been taken, using observations of lensing

[2]This agreement also provides quantitative support for the hypothesis that, in MOND (or indeed any alternative gravity theory), photons experience twice the deflection of massive particles moving at the speed of light.

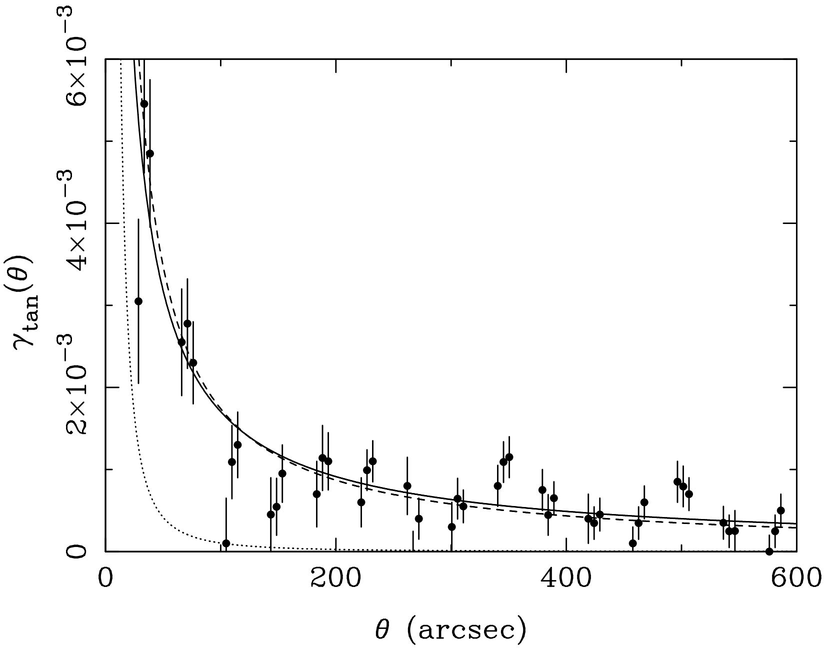

Figure 1: The mean shear, $\gamma_{\rm tan}(\theta)$, around foreground galaxies in the g', r' and i' bands, as measured by Fischer et al. (2000) is compared to various theoretical predictions. In each bin the data in the three bands (which are offset for clarity) are strongly correlated as the errors are dominated by the sample noise in the orientations of the background galaxies. The three models shown are: the best-fit power law (solid line); the MONDian prediction (dashed line); and the Newtonian result if there is no dark matter (dotted line).

to constrain the form of MONDian light deflection. The cleanest way of doing this is to use galaxy-galaxy lensing data to show that the deflection of photons is simply twice the deflection that would be experienced by a massive particle moving at the speed of light. Thus, a relativistic MONDian theory must have a great deal in common with GR.

With one more part of a complete theory in place a number of new observational tests become available. The clearest relate to "simple" lenses: situations in which there is a single, isolated deflector that has no internal structure on the scales of interest. Microlensing within the local group fulfills these criteria, although the typical impact parameters are so small that it is only the low-magnification tails of the light-curves that are of interest. However microlensing by cosmologically distant deflectors offers a good opportunity to confirm or reject MOND. Several programmes to measure low optical depth microlensing of high-redshift quasars are underway (Walker 1999; Tadros, Warren & Hewett 2001), but thus far no events have been observed. The only (probable) example of cosmological microlensing by an isolated deflector observed to date is the serendipitous detection of a peak in the light curve of gamma ray burst 000301C (Garnavich, Loeb & Stanek 2000), but the photometry is not of sufficient quality to differentiate between MOND and GR.

Further observations of galaxy-galaxy lensing offer the most likely tests of MONDian lensing in the near future. Any asymmetry in the distortions (c.f. Natarajan & Refregier 2000) would be at odds with a no-dark matter theory, and there is also the possibility of measuring an outer cut-off in the shear signal. This must eventually come from the influence of secondary deflectors along the line-of-sight, but could also signify a putative return to a Newtonian regime in the ultra-weak acceleration limit. If MOND is not contradicted by any of the above observations, more complex situations should be investigated. Multiple or extended deflectors must also be able to explain

observed shear fields and cases of multiple imaging without recourse to invisible mass.

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